Radar wind climatology of the quarterdiurnal tide in the mesopause region over Central and Eastern Europe

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Summary: While the diurnal, semidiurnal and terdiurnal tides in the mesosphere/lower thermosphere (MLT) have been observed from the ground and from satellites, the quarterdiurnal tide (QDT), with a period of 6 hours, has been investigated on a few occasions only. Therefore, meteor radar observations of horizontal winds in the MLT near 90 km at Collm (51°N, 13°E) and Obninsk (55°N, 37°E) have been used to analyse the seasonal variability of the QDT at middle latitudes. At both sites the zonal amplitudes show a clear maximum in winter and another one during spring. The meridional amplitudes are weaker, but show a similar seasonal cycle. Generally amplitudes are not large and maximise at 3.5 m/s for the zonal amplitude on a climatological mean. Amplitudes and phases, the latter expressed in local time, at Collm and Obninsk are similar, indicating that most of the observed 6-hour oscillation at higher midlatitudes is due to the migrating QDT. Obninsk amplitudes show an interdecadal variation with smaller values during the 1990s and larger ones during the 2000s.

Zusammenfassung: Während die ganztägigen, halbtägigen und dritteltägigen Gezeiten in der Mesosphäre und unteren Thermosphäre (mesosphere/lower thermosphere, MLT) vergleichsweise häufig durch bodengebundene und Satellitenmessungen untersucht wurden, gilt dies nur sehr eingeschränkt für die vierteltägigen Gezeiten (quarterdiurnal tides, QDT). Daher werden hier Radarmessungen des horizontalen Windes über Collm (51°N, 13°E) und Obninsk (55°N, 37°E) bei 90 km Höhe herangezogen, um den mittleren Jahresgang der QDT in mittleren Breiten zu analysieren. Es zeigt sich, dass an beiden Messstationen ein Maximum der Amplituden im Zonalwind auftritt, begleitet von einem weiteren im Frühjahr. Die Amplituden sind nicht sehr groß, und betragen für den Zonalwind 3-4 m/s im langzeitigen Mittel im Winter. Die Amplituden im meridionalen Wind sind etwas geringer, zeigen aber einen ähnlichen Jahresgang. Amplituden und Phasen, letztere ausgedrückt in lokaler Zeit, sind über Collm und Obninsk ähnlich, was auf einen bedeutenden Anteil der migrierenden QDT hinweist. Die Amplituden über Obninsk weisen eine interdekadische Variation auf, mit geringeren Amplituden in den 1990ern und größeren nach den Jahr 2000.

1. Introduction

The dynamics of the mesosphere and lower thermosphere (MLT) are strongly influenced by atmospheric waves, including the solar tides with periods of a solar day and its harmonics. Their wind amplitudes usually maximise around 100-120 km. In these regions, their amplitudes are of the order of magnitude of the mean wind. As a result, the solar tides drive the global circulation and more accurate knowledge leads to a better understanding of the wind fields in the MLT. Shorter period waves often have smaller amplitudes, so that in the past the diurnal tide (DT), the semidiurnal tide (SDT), and also the terdiurnal tide (TDT) has been considered. The quarterdiurnal tide (QDT), however, although it also forms an integral part of the middle and upper atmosphere dynamics, has attained much less attention, mainly due to its small amplitude in the MLT.

While near the surface the 6 hr-oscillation at times can be a major component e.g. in barographic records (e.g., Warburton and Goodkind, 1977), the QDT amplitude in the MLT is generally substantially smaller than the one of the DT, SDT and also the TDT. Consequently, only few attempts to determine the QDT characteristics from radar or satellite has been made so far, and very few studies included the modelling of the QDT global structure and its sources. Considerable amplitudes have been reported by Walterscheid and Sivjee (1996, 2001) in the high-latitude winter, but they concluded that these were zonally symmetric tides and not migrating ones. Kovalam and Vincent (2003) analysed medium frequency (MF) radar winds over Adelaide, Australia and Davis, Antarctica. They found signatures of 6- and 8-hr tides, but belonging to a wavenumber 1 so that they concluded that these oscillations are not thermally forced but may be owing to non-linear interactions. Smith et al. (2004) analysed the QDT over Esrange, Sweden, and found that the QDT wind amplitudes on a monthly average may exceed 5 m/s at 97 km altitude and maximise in winter. They also performed numerical simulations that revealed that much of the wintertime QDT is forced by the 6-hour harmonic of solar heating, but without direct forcing the tide still appears and also maximises in winter. Liu et al. (2006) noted a 6-hr signature in MF radar data over Wuhan, China, but mainly in their upper height gates above 90 km. 6-hr waves have also been reported in Lidar temperatures (She et al., 2002), but their amplitudes are also small.

The 6-hr harmonics of ozone heating rates have been calculated from Aura/MLS observations by Xu et al. (2012), who noted that the main 6-hr forcing during solstice is in the winter hemisphere. Xu et al. (2014) analysed nonmigrating tides from TIMED/SABER observations. They confirmed earlier results that the QDT is largest in winter, and found indications that the nonmigrating QDT is likely to be forced by nonlinear interaction between the DT and TDT, while the interaction between stationary planetary waves and the QDT is weak, likely because of the small amplitudes of the migrating QDT. In a further study, Liu et al. (2015), again using TIMED/SABER data, analysed the migrating QDT between 50°S and 50°N in the middle atmosphere. From their analyses they considered both direct heating and tidal interaction as possible sources of the QDT. The seasonal/latitudinal structure of their QDT is complex; generally, the seasonal cycle exhibits a maximum in winter and also in spring. Concerning the latitudinal distribution, there are three maxima between 50°S and 50°N. Such a complex structure (and another maximum near 60° of the winter hemisphere, which cannot be seen by SABER) has also been modelled by Smith et al. (2004).

To summarise, to date there are rather few analyses of the QDT both locally and on a global scale, and available datasets should be used to contribute to our knowledge of the climatology of the QDT in the MLT. In addition, more information on the contribution of migrating and nonmigrating waves to the QDT is required. Furthermore, the forcing mechanisms of the QDT are still unclear and have to be investigated further. In this paper we analyse the QDT signature in midlatitude MLT winds at about 90 km altitude using two radars at Collm (51°N, 13°E) and Obninsk (55°N, 37°E). In section 2 the radar systems are briefly described, the climatology of the QDT based on these measurements is presented in section 3, and in section 4 the interannual and decadal variability of QDT amplitudes is analysed. Section 5 concludes the paper.

2. Description of the measurements

2.1 Obninsk meteor radar

Measurements of the horizontal winds in the MLT region over Obninsk from 1980 to 2012, with some data gaps, have been analysed. The measurements have been performed using the meteor radar technique and they were described in several papers (e.g., Portnyagin et al., 2006) in detail. The horizontally pointing meteor radar installed at Obninsk does not provide height information of the meteor echo, and the results of measurements are referred to an average height of 90 km. This is justified since the daily average height of the underdense sporadic meteors is quite stable for radars with frequencies from 30 to 50 MHz. The Obninsk radar delivers 1000-3000 useful radio echoes per day for sounding in the zonal direction.

The meteor radar at Obninsk provides results of wind measurements for two zonal directions (radar beams pointing towards the west and the east). We used arithmetic means of the corresponding values. The technique of these measurements was the same until autumn 2007 (for more details see Merzlyakov et al., 2009, 2015), when the radar frequency was changed from 33.6 MHz to 46.3 MHz. During three months (August-October 2007) both radars measured winds simultaneously. Only a small shift in the zonal wind speeds was seen after replacement of a receiver, transmitter and antennas, which should not affect tidal amplitudes and phases.

The original data are hourly mean horizontal wind speeds. The QDT zonal and meridional amplitudes A_z and A_m, as well as their phases T_z and T_m were calculated for monthly data with a least squares fit with a monthly mean and 24-, 12-, 8-, and 6-hour tidal harmonics. The phases are given as the local time of the eastward or northward wind maximum, respectively. Monthly mean 6-hr amplitudes are presented in Figure 1. From 1998 through 2012 a continuous time series is available. One may also see that the amplitudes during the 1990s tend to be smaller than before and after that time interval.

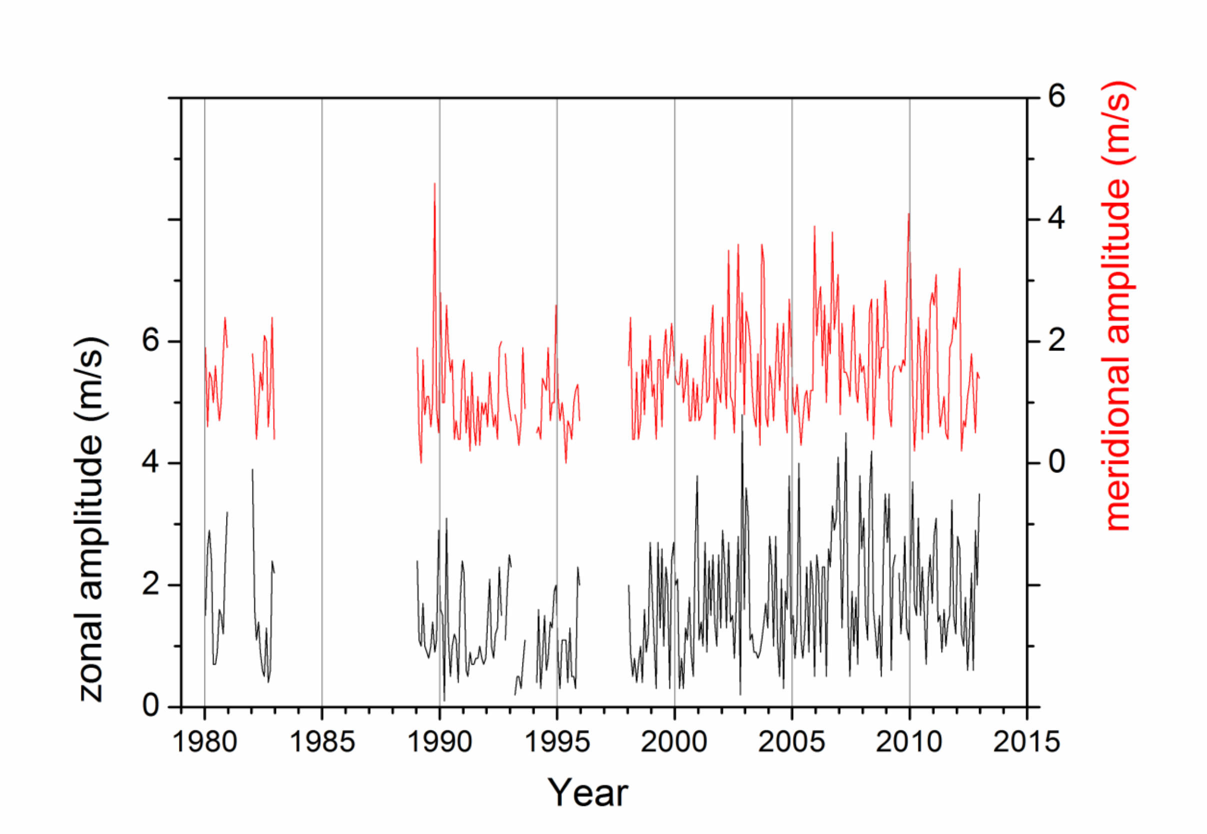

Fig. 1: Monthly zonal (black) and meridional (red) amplitudes of the 6-hour oscillation over Obninsk.

2.2 Collm SKiYMET meteor radar

The VHF SKiYMET meteor radar located at Collm has been operated nearly continuously since the summer of 2004. The radar uses the Doppler shift of the reflected radio wave from ionized meteor trails to obtain radial velocities along the line of sight of the radio wave. The radar operates at a frequency of 36.2 MHz. The transmitting antenna is a vertically pointing 3-element Yagi so that meteor echoes are registered for each azimuth angle. The receiving interferometer consists of five 2-element Yagi antennas arranged as an asymmetric cross to allow determination of azimuth and elevation angle from phase comparisons of the individual receiver antenna pairs. Together with range measurements the meteor trail position is detected. The radar and the data collection procedure are described in Hocking et al. (2001) and Jacobi et al. (2015).

The radar delivers half hourly mean horizontal wind values through projection of the horizontal half-hourly wind components to the individual radial winds under the assumption that vertical winds are small. Meteors at altitudes between 80 and 100 km are used here to calculate half-hourly winds. Since only very few meteors are registered outside this height range, this approach practically leads to winds measured without height finding, and the results are comparable to those measured with the Obninsk configuration. Note that the meteor radar standard analysis procedure delivers vertical profiles of wind parameters (e.g. Jacobi, 2012). Through the effective vertical averaging performed here there is a tendency of reducing especially solar tides owing to their vertical phase gradient. Monthly mean prevailing winds and tidal parameters are calculated by a least squares fit of one month of half-hourly mean winds on model winds including the mean (prevailing) wind and 24-, 12-, 8-, and 6-hour tidal harmonics.

3. Climatology of the quarterdiurnal tide

8-year means including data from 2005 through 2012 have been constructed by arithmetic averaging of QDT amplitudes, and vector averaging of the tidal phases. Arithmetic averaging of amplitudes has been preferred here against vector averaging, because in the presence of phase shifts vector averaging will result in underestimation of the "most probable" amplitudes (e.g., Manson et al., 1983; States and Gardner, 2000). The described procedure has been applied for both horizontal wind components. Zonal mean amplitudes are shown in Fig. 2, while meridional amplitudes are presented in Fig. 3. Relative tidal amplitude differences ΔA have been calculated from the monthly mean amplitudes:

$$\Delta A = 2\,\frac{A_{zonal} - A_{meridional}}{A_{zonal} + A_{meridional}}\,, \tag{1}$$

while mean zonal-meridional phase differences $\Delta\varphi = T_z - T_m$, given in degrees, have been calculated from the monthly mean phases. Positive $\Delta\varphi$ values indicate that the meridional component leads the zonal one, and $\Delta\varphi = 90°$ together with $\Delta A = 0$ indicate right-hand circular polarisation of the tidal wave. The amplitude and phase differences are shown in Fig. 4.

The zonal amplitudes (Fig. 2, left panel) show maxima during winter and during spring, which is seen for both Collm and Obninsk. Maximum amplitudes during winter have also been reported by Smith et al. (2004) for high northern latitudes. The maximum amplitudes over Collm amount to 3.5 m/s on a climatological average, which is slightly larger than those reported by Smith et al. (2004), however, their data refer to higher latitudes. The Collm winter zonal amplitudes are slightly smaller than Obninsk ones, while for late summer the Collm amplitudes are slightly larger than the ones over Obninsk. However, the amplitudes are small and the differences should not be overinterpreted. The meridional amplitudes (Fig. 3, right panel) show a similar behaviour over Collm and Obninsk, except for December.

For most months, the Collm and Obninsk amplitudes agree within one standard deviation. During winter, zonal amplitudes tend to be larger than meridional ones, which is also visible in the relative differences ΔA according to Eq. 1 (left panel of Fig. 4). In summer, ΔA is small and the zonal and meridional amplitudes are of similar magnitude.

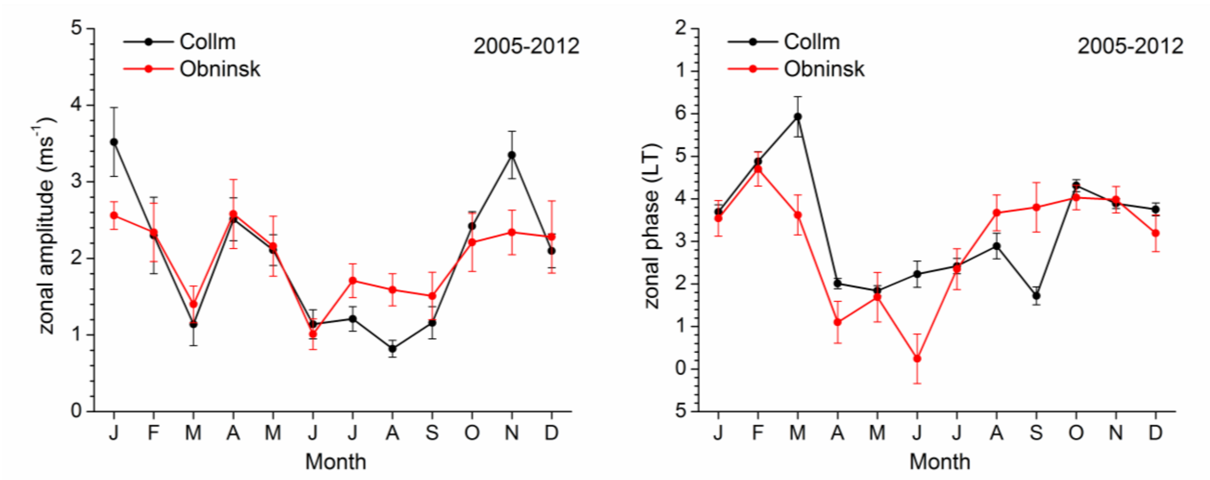

Fig. 2: 8-year mean monthly mean zonal amplitudes (left panel) and phases (right panel) at Collm and Obninsk. Error bars denote standard error of the monthly means.

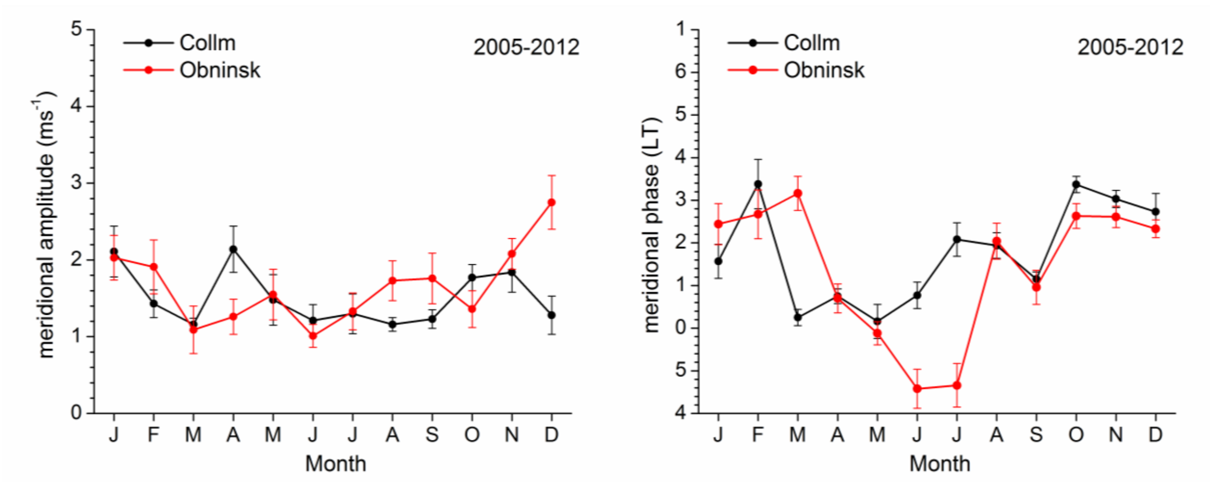

Fig. 3: As in Fig. 2, but for the meridional component.

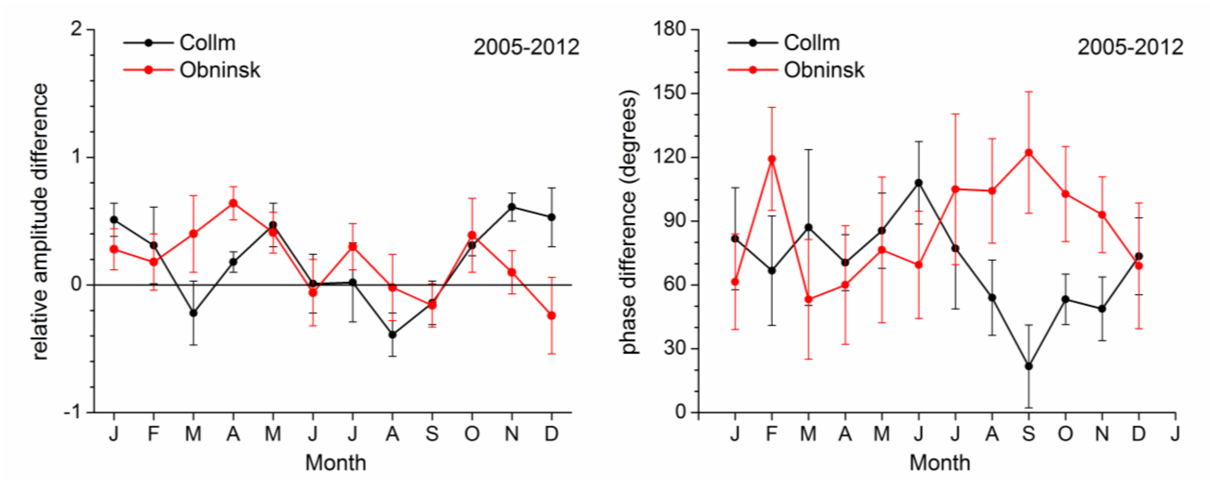

Fig. 4: Left panel: relative amplitude difference ΔA after Eq. 1. Right panel: Difference Δφ between the zonal and meridional phases, positive values indicate that meridional oscillations lead the zonal ones. Data are 8-year means calculated from monthly means. Error bars denote standard error of the monthly means.

The zonal phases (right panel of Fig. 2) differ by about 2 hours between summer and winter. This behaviour is found for both Obninsk and Collm, and it is also visible for the meridional component (right panel of Fig. 3). Generally, phases over Collm and Obninsk agree well, larger differences are usually found when the amplitudes are small, e.g., in March or during summer. This, together with similar amplitudes, indicates that the major part of the 6-hour oscillations seen at Collm and Obninsk are owing to a migrating tide.

Comparison of the right panels of Figs. 2 and 3 shows that on an average meridional phases are earlier than the zonal ones, i.e. the meridional winds lead the zonal ones. Fig. 4 (right panel) shows that from December through July the phase difference is between 60 and 90 degrees which, together with not too large differences of the amplitudes, indicate a substantial circularly polarized component.

4. Interannual and long-term variability

To give an impression on the interannual variability of the 6-hour oscillation, in Fig. 5 we show 3-monthly means of the amplitude, which is the square-root of the sum of the squared zonal and meridional amplitudes. According to the climatological means in Figs. 2 and 3, maximum and minimum values are expected in November-January (NDJ) and June-August (JJA), respectively. Therefore, the NDJ/JJA values are highlighted by solid/open circles in Fig. 5.

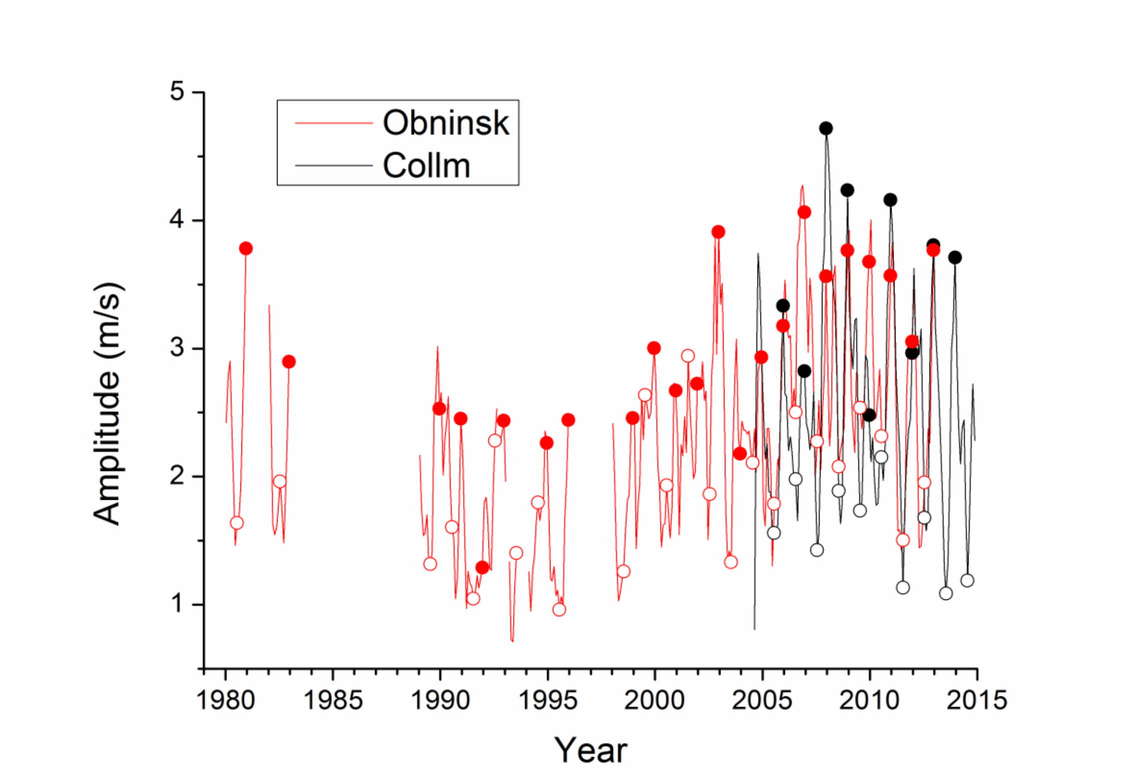

Fig. 5: 3-monthly mean amplitudes over Obninsk and Collm. November-January values are highlighted as solid circles, while June-August means are shown as open circles.

There is a data gap around the middle 1980s, and a smaller one in the 2nd half of the 1990s, nevertheless one can see a tendency for somewhat larger amplitudes in the early 1980s than in the 1990s. In the 1990s amplitudes both during winter and summer tend to be smaller than during the other time intervals under investigation. After 2000, amplitudes both in winter and summer tend to increase again, but there is some additional variability during winter, and in some cases the amplitudes are rather small. After 2000, there is a tendency that the summer amplitudes decrease again.

5. Conclusions

Meteor radar observations of horizontal winds in the MLT near 90 km at Collm and Obninsk have been used to analyse the seasonal variability of the QDT at middle latitudes. At both sites the zonal and meridional amplitudes show a maximum in winter and another one during spring. Collm amplitudes reach values of about 3.5 m/s in zonal wind and 2 m/s in meridional wind. At Obninsk zonal amplitudes are slightly smaller (up to 2.6 m/s). Obninsk meridional amplitudes exceed those in Collm in December with 3 m/s on a climatological average.

Generally, amplitudes and phases at Collm and Obninsk are similar, and larger phase differences are usually only found when the amplitudes are small (e.g., in March or during summer), indicating that much of the observed 6-hour oscillation at higher midlatitudes is due to the migrating QDT. Phase differences between zonal and meridional phase are near 60-90° for most months. This, together with small relative amplitude differences, indicates a substantial circularly polarized component.

Obninsk amplitudes show an interdecadal variation with smaller values during the 1990s and larger ones during the 2000s. Collm amplitudes indicate that after 2010 the amplitudes may decrease again.

Acknowledgements

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References

Hocking, W. K., Fuller, B., Vandepeer, B., 2001: Real-time determination of meteor-related parameters utilizing modern digital technology, J. Atmos. Sol.-Terr. Phys., 63, 155-169, doi: 10.1016/S1364-6826(00)00138-3.

Jacobi, Ch., 2012: 6 year mean prevailing winds and tides measured by VHF meteor radar over Collm (51.3°N, 13.0°E), J. Atmos. Sol.-Terr. Phys., 78–79, 8–18, doi: 10.1016/j.jastp.2011.04.010.

Jacobi, Ch., Lilienthal, F., Geißler, C., Krug, A., 2015: Long-term variability of mid-latitude mesosphere-lower thermosphere winds over Collm (51°N, 13°E), J. Atmos. Sol.-Terr. Phys., 136, B, 174–186, doi: 10.1016/j.jastp.2015.05.006.

Kovalam, S., Vincent, R. A., 2003: Intradiurnal wind variations in the midlatitude and high-latitude mesosphere and lower thermosphere, J. Geophys. Res., 108, 4135, doi: 10.1029/2002JD002500.

Liu, R., Lu, D., Yi, F., Hu, X., 2006: Quadratic nonlinear interactions between atmospheric tides in the mid-latitude winter lower thermosphere, J. Atmos. Sol.-Terr. Phys., 68, 1245–1259, doi: 10.1016/j.jastp.2006.03.004.

Liu, M. H., Xu, J. Y., Yue, J., Jiang, G. Y., 2015: Global structure and seasonal variations of the migrating 6-h tide observed by SABER/TIMED, Science China: Earth Sciences, doi: 10.1007/s11430-014-5046-6.

Manson, A. H., Meek, C. E., Gregory, J. B., 1983: The semi-diurnal tide at the equinoxes - MF radar observations for 1978-1982 at Saskatoon (52°N, 107°W), J. Atmos. Sci., 40, 969-976.

Merzlyakov, E. G., Jacobi, Ch., Portnyagin, Yu. I., Solovjova, T. V., 2009: Structural changes in trend parameters of the MLT winds based on wind measurements at Obninsk (55°N, 37°E) and Collm (52°N, 15°E), J. Atmos. Sol.-Terr. Phys., 71, 1547-1557.

Merzlyakov, E. G., Jacobi, Ch., Solovjova, T. V., 2015: The year-to-year variability of the autumn transition dates in the mesosphere/lower thermosphere wind regime and its coupling with the dynamics of the stratosphere and troposphere, J. Atmos. Sol.-Terr. Phys., 122, 9-17, doi:10.1016/j.jastp.2014.11.002.

Portnyagin, Yu. I., Merzlyakov, E. G., Solovjova, T. V., Jacobi, Ch., Kürschner, D., Manson, A., Meek, C., 2006: Long-term trends and year-to-year variability of mid-latitude mesosphere/lower thermosphere winds, J. Atmos. Sol.-Terr. Phys., 68, 1890-1901.

She, C. Y., Chen, S., Williams, B. P., Hu, Z., Krueger, D. A., 2002: Tides in the mesopause region over Fort Collins, Colorado (41°N, 105°W) based on lidar temperature observations covering full diurnal cycles, J. Geophys. Res., 107, D18, 4350, doi: 10.1029/2001JD001189.

Smith, A. K., Pancheva, D. V., Mitchell, N. J., 2004: Observations and modeling of the 6-hour tide in the upper mesosphere, J. Geophys. Res, 109, D10105, doi: 10.1029/2003JD004421.

States, R. J., Gardner, C. S., 2000: Thermal structure of the mesopause region (80–105 km) at 40°N latitude. Part II: Diurnal variations, J. Atmos. Sci., 57, 78-92.

Walterscheid, R. L., Sivjee, G. G., 1996: Very high frequency tides observed in the airglow over Eureka (80˚), Geophys. Res. Lett., 23, 3651−3654, doi: 10.1029/96GL03482.

Walterscheid, R. L., Sivjee, G. G., 2001: Zonally symmetric oscillations observed in the airglow from South Pole station, J. Geophys. Res., 106A, 3645−3654, doi: 10.1029/2000JA000128.

Warburton, R. J., Goodkind, J. M., 1977: The influence of barometric-pressure variations on gravity, Geophys. J. R. Astr. Soc., 48, 281-292.

Xu, J., Smith, A. K., Jiang, G., Yuan, W., Gao, H., 2012: Features of the seasonal variation of the semidiurnal, terdiurnal and 6-h components of ozone heating evaluated from Aura/MLS observations, Ann. Geophys., 30, 259–281, 2012, doi: 10.5194/angeo-30-259-2012.

Xu, J., Smith, A. K., Liu, M., Liu, X., Gao, H., Jiang, G., Yuan, W., 2014: Evidence for nonmigrating tides produced by the interaction between tides and stationary planetary waves in the stratosphere and lower mesosphere, J. Geophys. Res. Atmos., 119, 471–489, doi: 10.1002/2013JD020150.